Journal of
Flood Risk Management

Compartmentalisation: flood consequence reduction by splitting up large polder areas

F. Klijn, N. Asselman and H. Van der Most

Deltares|Delft Hydraulics, Delft, The Netherlands

Correspondence: Frans Klijn, Deltares|Delft Hydraulics, PO Box 177, NL 2600 MH Delft, The Netherlands
Email: frans.klijn@deltares.nl

DOI:10.1111/j.1753-318X.2009.01047.x

Key words
Flood risk management; flood consequences; policy analysis; cost benefit analysis; the Netherlands.

Abstract

River and coastal floodplains are often protected by vast systems of connected embankments. In the Netherlands, about 55% of the country is protected in this way, by some 3600 km of primary defences. The protection level is probably the highest in the world, and annual mean flood risks are low. Nevertheless, the consequences of a major flood event might be unacceptable. This is a reason to consider whether and how the consequences of floods could be reduced in a cost-effective manner. Splitting up large polder areas into smaller portions, the so-called compartmentalisation, would reduce the area subject to flooding, and thus the economic damage, the number of people exposed and the fatality risk. We carried out a policy analysis for the national authorities in order to establish whether, where and under which conditions a further compartmentalisation of the country would be desirable. This paper gives some results, discusses our experiences in four case studies and finally focuses on the fundamental questions of assessment and the trade-off between better flood protection and the benefit/cost ratio of reducing consequences.

Introduction

The EU directive on flood risk assessment and management requires that member states assess their flood risks, and plan their future flood risk management (EU, 2007). Obviously, a low-lying country such as the Netherlands already has a certain tradition in assessing its flood risks and in taking measures for their reduction. This tradition, however, has primarily focused on protection against floods. As a result, the protection levels in the Netherlands are the highest in the world, with embankments having been designed for flood and storm probabilities varying from 1:1250 per year along the rivers to 1:10 000 per year along the coast. When the embankments are well kept, the actual flood probabilities are generally significantly lower than the design standards (Klijn *et al*., 2004). This translates into the fact that, despite the growing population and steadily increasing economic value of the protected areas (Klijn *et al*., 2007), the protection standards in the majority of the country are still fully adequate from an economic cost–benefit perspective (Van der Most *et al*., 2006; confirmed by Kind *et al*., 2008).

Modern approaches to flood risk management can be regarded as an evolution from flood defence via flood control and flood management to comprehensive flood risk management (Samuels *et al*., 2006; Klijn *et al*., 2008). Against a background of risk having been defined as the product of flood probability and flood consequence (FLOODsite, 2005), this approach recognises the need to equally consider measures to reduce flood probability, exposure to floods and flood consequences (FLOODsite, 2009). For the Netherlands government, this is also the reason to seriously consider measures that may reduce the consequences of flood events, despite their low probability (Ministry of Transport, Public Works and Water Management, 2008). The main reason is that the sheer magnitude of the consequences may be regarded unacceptable. Among the measures taken into consideration are evacuation, placing sand bags, flood proofing, etc., but also reduction of the exposed area by compartmentalisation or embankments that remain intact when overtopped (Table 1).

In order to be able to decide on which measures to take, all possible measures must be evaluated seperately, as well as in comparison with each other. Of all the possible measures, compartmentalisation seemed attractive in earlier research (Vis *et al*., 2003) and was also found to be one of the most cost-effective measures along the Rhine River branches (Ministry of Transport, Public Works and Water Management and Ministry of Interior and Kingdom Relations, 2006). It had, however, not been thoroughly assessed for

Table 1 Examples of measures aimed at reducing the flood probability and/or at reducing the consequences of flooding

Preventive flood risk management	Flood event management
Reduction of flood probability	
Embankments, new and strengthening	Sand bags
	Temporary strengthening of weak spots
Strengthening dunes	
Storm surge barriers	
Room-for-rivers measures	
Beach nourishment	
Reduction of consequences (*exposure and vulnerability*)	
Compartmentalisation	Warning
Spillways and overflow-resistant embankments	Evacuation
	Rescue of people and property
Dedicated protection of vital infrastructure	
Development planning	
Flood proofing	

the Netherlands as a whole, which was a reason for the government to commission a study.

The objective of the study was to assess whether, where and under which conditions compartmentalisation would be a sensible measure to reduce the remaining flood risk. Where earlier studies focused on the fluvial plains only, this study had to consider floods from various sources: coastal, estuarine and fluvial alike. As it is connected to the government's revision of the Netherlands' policy for flood risk management (Water Safety 21st Century), it methodologically follows the risk approach adopted for that programme. This matches the approach advocated by the EU-Integrated Project FLOODsite (FLOODsite, 2009; Samuels *et al*., 2009).

In this paper, we first explain the ideas behind compartmentalisation. Then, we present the main findings of the study on three different research activities: (1) review of existing knowledge, (2) nation-wide assessment of attractiveness and (3) exploratory analysis in case-study areas. Then we discuss some of the difficulties we encountered during the research, and finally we provide a brief outlook on how our findings may affect the policy.

Compartmentalisation: principle and objective

The primary objective of compartmentalisation is to diminish the surface area that can be flooded due to one single flood event resulting from the failure of an embankment. The flood-prone part of the Netherlands is divided into 53 so-called dike-ring areas – areas entirely surrounded by embankments or by embankments and high ground – which have protection levels ranging from 1:1250 per year to 1:10 000 per year. These dike-ring areas, however, have very different sizes ranging from $< 1\,km^2$ to large ones of about 660, 1500, 2200 and even 4900 km^2. Similar physiographical settings, although usually less extensive, are found along various coasts in Europe [German Bight, East Anglia (the Fens), Po Valley] and elsewhere (southeastern United States, Bangladesh). The hypothesis is that flood damage and number of people affected by a flood are, for a large part, related to the surface area that is being flooded, and that reducing this area may significantly reduce the flood consequences.

Compartmentalisation literally means splitting up into smaller portions. The principle is applied in various other situations, where risk is an important issue, e.g. shipping or fire prevention. In shipping, water-tight compartments are often applied to prevent ships from sinking when a leak occurs – i.e. for their own sake – whereas in oil tankers the tanks are divided to prevent the entire oil from spilling due to a single leak only – i.e. to protect the external environment. Buildings are applied with fireproof walls and automatically closing fire doors to prevent the fire from spreading. And in forestry, parcels are divided by roads to – again – firstly, prevent a fire from rapid and easy spreading, and, secondly, to allow easy access for the fire brigade.

In 1953, the Netherlands experienced a major flood disaster, caused by a storm surge, and resulting in 1836 fatalities and over 72 000 people rendered homeless (Gerritsen, 2005). Many polders were then flooded, but in many cases not entirely, because the protected areas consisted of many small compartments, which were the by-product of a history of recurrent land reclamation (Figure 1). This experience made the Delta Committee (1961) advise the government to not only focus on better protection – although that was their main advice – but also to divide large polder areas into smaller ones. This element of advice has been neglected in the following decades and almost forgotten since. Recent flood simulations (Asselman, 2006), however, show that even remnants of old embankments are still very effective in slowing down the flooding process, and in limiting the flood extent (Figure 2).

In flood risk management, compartmentalisation thus aims to reduce flood risks by reducing the consequences of any flood event. In a strict sense, compartmentalisation implies dividing large dike-ring areas into smaller ones by dividing embankments, which are equally high as the primary defence. But several variations are possible. For example, an attempt to influence the flooding process and pattern by merely slowing down the flood water or by guiding it to less flood-prone areas can be achieved through embankments much lower than the primary defences (Asselman, 2006), but also by making compartments of very different sizes, sometimes resulting in the 'lines of secondary defence' that keep the larger part dry, or instead allow large rural areas to be flooded while keeping small urban areas dry by 'city rings'.

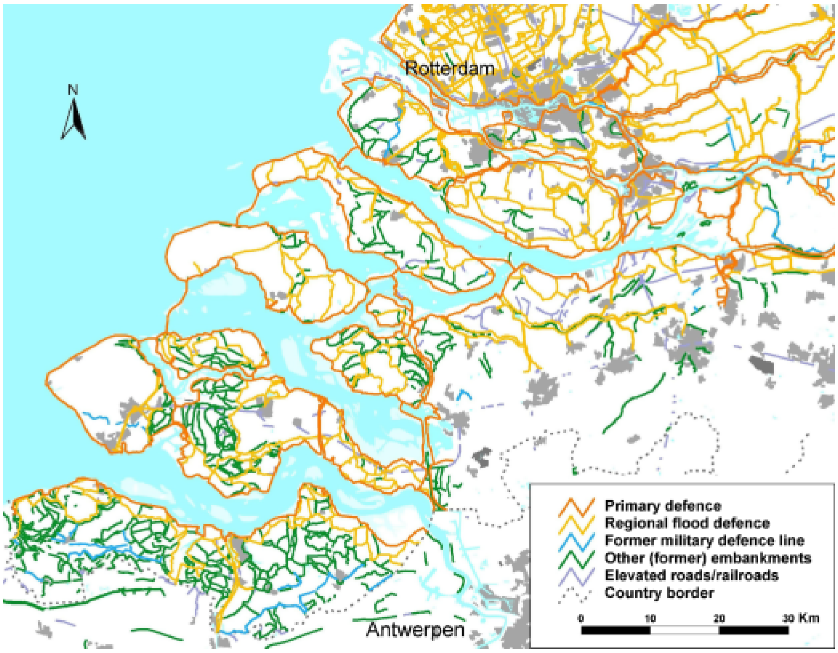


Figure 1 A history of land reclamation has led to an intricate network of embankments in the southwest of the Netherlands, which are only partly maintained.

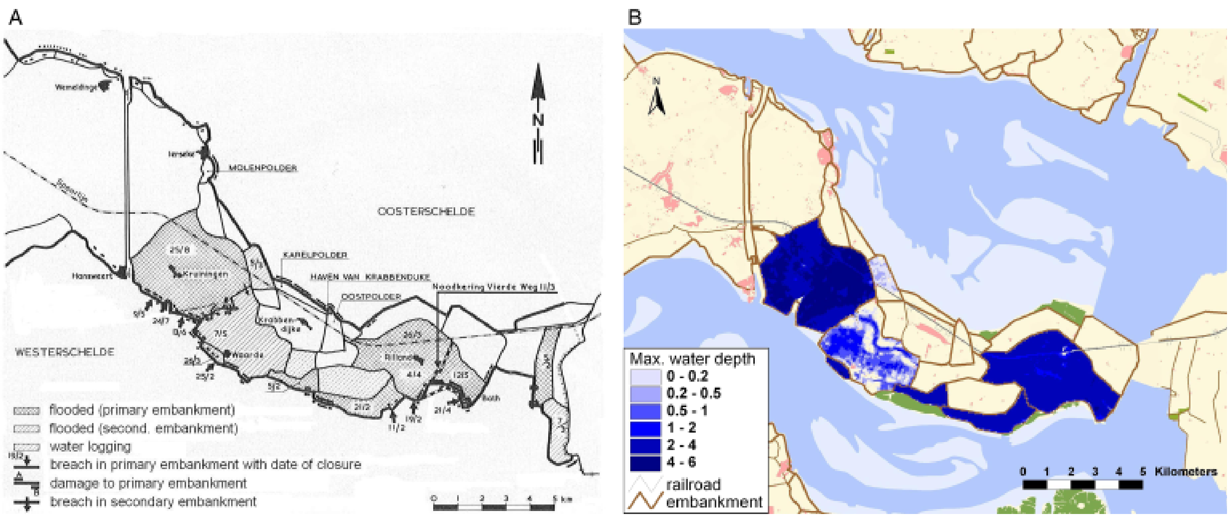


Figure 2 Areas flooded in a dike-ring area in the southwest Netherlands during the 1953 disaster (a) and flood pattern and depth resulting from breaches in the same locations as simulated with SOBEK 1D-2D (b), both showing the influence of former flood defences on flooded surface area (sources: Rijkswaterstaat 7 KNMI, 1961 and Asselman, 2003).

Ascertained and supposed advantages and disadvantages of compartmentalisation

The advantages and disadvantages of compartmentalisation were investigated by (1) a historic review of almost 1000 years of flood defence and connected societal and scientific disputes (Van Heezik, 2008b), (2) a literature review of recent research into controlling flooding processes and patterns (a.o. Verwijmeren, 2002; Vis *et al.*, 2003; De Bruijn, 2005; Kok *et al.*, 2005; Asselman, 2006; De Bruine, 2006; Theunissen, 2006; De Bruijn *et al.*, 1961) and (3) a brief inventory of considerations in other risk domains (shipping, fire).

This yielded the following list of advantages, or at least presumed or conditional advantages:

- reduction of the flooded surface area and, hence, economic damage and the number of people affected;
- slower growth of breaches because of backwater effects and smaller discharges through the breach;
- respite, allowing counter-measures to be taken;
- easier evacuation of smaller numbers of people over shorter distances;
- refuge for people and cattle on the additional embankments, as well as safe evacuation routes.
- reduction of flood duration, especially in tidal areas because breaches can be closed more easily when the tidal flow volumes and currents are reduced.

Possible disadvantages of compartmentalisation that were identified comprised the following:

- increased risk of loss of life in smaller compartments, because of faster water-level rise and greater maximum water depth;
- loss of scarce space, which is needed for the construction of a secondary defence or dividing embankment, especially in densely populated areas;
- destruction of natural and cultural landscape values;
- high costs of implementation and maintenance, which were better spent on the primary defences.

Some of these advantages and disadvantages were recognised both in past centuries and nowadays alike. But there are also some remarkable differences. For example, the trust in the primary defences was much less in the past, which was the reason to argue for compartmentalisation for the eventuality that the primary defences would fail well before the maximum water level would be achieved. Nowadays, the trust in the primary defences is such that dividing embankments are regarded useful especially to reduce the residual risk, which is connected with design flood levels being exceeded.

Here, we shall not dwell on all recognised advantages and disadvantages, as many speak for themselves. Some may do with some clarification and distinction, however. Firstly, the reduction of the flooded surface area and, hence, economic damage and the number of people affected was already mentioned as being the main goal of compartmentalisation. However, when the amount of water that can enter an area is limited, like with smaller rivers or lakes, a smaller surface area may imply greater water depths. As the largest percentage of maximum potential damage in most land-use functions is already incurred at small water depths (cf. depth-damage curves, e.g. Jonkman *et al.*, 2008), the gains of smaller flooded surface area usually outweigh the losses caused by greater water depths.

In contrast, the probability of fatalities depends much more on water level rise rate and water depth (Jonkman *et al.*, 2008; Lumbroso *et al.*, 2008), than it does on surface area. Loss of life is especially expected close to breaches (little warning time and response time; high flow rates) and in small deep polders where the water is obstructed (rapid water level rise; disturbed eye-ball navigation) (De Bruijn and Klijn, 2009). Both water level rise rate and water depth are usually high in small compartments. Making compartments too small, therefore, does not seem advisable.

However, small compartments usually also contain less people, and evacuation routes to safe ground are generally shorter. The four largest dike-ring areas in the Netherlands contain about 400 000, 950 000, 3 200 000 and 1 000 000 inhabitants, respectively. Effectively evacuating such numbers of people is not regarded feasible. Dividing such dike-ring areas may have the advantage of easier and faster evacuation of less people over smaller distances.

The reinforcement and renewal of many flood defences along the Netherlands' rivers raised massive public opposition in the 1970s and 1980s, because of the negative impacts on the cultural heritage and natural values of the riverine landscape [the responsible authorities were then addressed as 'Attila on the Bulldozer' (Van Heezik, 2008a)]. Currently, the authorities are so aware of this possibility that they are very reluctant to even suggest to build new embankments. We should, however, realise that the Netherlands' landscape partly owes its special character to the intricate network of embankments and canals. Embankments from the past are generally highly valued, not in the least because of their function in recreational cycling routes, where they allow grand views over rivers and coast (Photo 1). And many new linear infrastructures are being implemented for other reasons, such as roads, noise barriers, etc. Combining flood defence functions with other such functions may really enhance landscape values, as we shall discuss later in this paper. In general, one might even argue that flood defence

Photo 1 Historic compartmentalisation embankment (Diefdijk) which has been raised several times since it was first built in 1284.

infrastructure designed by a committed and 'loving' designer may substantially contribute to the typically Dutch landscape character. The challenge on this issue obviously lies in a dedicated design for a specific situation.

Finally, the costs of additional embankments are often mentioned as a disadvantage, especially in relation to a supposed competition for funding of better protection by reinforcing the primary defences. It is obvious that decisions on compartmentalisation require a thorough and fair comparison with other flood risk-reducing measures, but this can be addressed by subjecting all possible measures to a (societal) cost–benefit analysis.

The above-mentioned advantages and disadvantages are mentioned in historic and recent reports. Partly they are based on research, but many merely act as arguments in debates, often without traceable underpinning. The ones that have been ascertained in analyses apply to specific situations but their applicability to other – different – situations is not obvious. And for some supposed (dis)-advantages, no quantitative underpinning will ever be possible, as they rely on trust and expectations. A comprehensive exploration of the issue, however, also requires including such argumentations.

Where and why compartmentalisation? A nationwide assessment

In order to establish where compartmentalisation might be sensible, a nationwide assessment was carried out. This was done for the major 53 existing dike-ring areas in the Netherlands, applying a land evaluation approach, which was aimed at assessing the 'suitability' for compartmentalisation. First, the relevance of compartmentalisation of each dike-ring area was evaluated. Secondly, the potential for cost-effectively splitting up the dike-ring areas was assessed. And thirdly, these two elements were combined into a final judgement of suitability – or rather 'potential' or 'attractiveness' – of each area for further compartmentalisation.

The *relevance* of compartmentalisation involved establishing where the reduction of economic damage and of potential number of fatalities would be desirable. This is especially the case in 'dangerously large dike-rings', where the expected societal benefit of compartmentalisation – in terms of avoided economic damage, avoided number of people affected, and lives saved – is probably largest. Relevance was, thus, evaluated by the following criteria:

- sheer size of flood-prone area (large dike-rings are likely to suffer more damage);
- the expected number of fatalities, the number of people affected and the expected economic damage;
- physiographical characteristics that determine the flooding process and pattern, such as the internal relief and the internal network of linear infrastructure (remains of flood defences, embankments along canals and other small water bodies, and other linear obstacles).

The evaluation, thus, encompassed a quest of figures on expected economic damage and potential number of fatalities per dike-ring, which were available from earlier studies (Klijn *et al.*, 2004, 2007; Table 2). For evaluation, the following thresholds were used: for size of the area 100 and 1000 km^2; for the number of people affected $\geq 100\,000$; for the expected number of fatalities ≥ 100; and for the expected damage 5 and 10 billion euros.

A physiographical characteristic, which is especially important, is the inclination of the terrain in the protected area. Polders on river floodplains, due to their geomorphological genesis, are often inclined towards the sea. This causes the water from an upstream dike breach to rapidly flow through; in the case of the Rhine and Meuse River floodplains in the Netherlands, this is towards the west. The upstream parts of such polders often become inundated only shallowly, whereas embankments perpendicular to the main river may function as obstacles and cause rapid water level rise (De Bruijn, 2005, pp 59–64). In such a case, there is a possible trade-off between a smaller flooded surface area versus greater flooding depths, as we found in one of the case studies.

On level terrain, such as the majority of the coastal plains and land reclamations, the flooding process is entirely different. Some deep polders are filled like bathtubs because of large differences between water level and ground level, whereas coastal plains, which lie at or slightly above the mean sea level, are inundated relatively slowly.

Finally, the degree of existing subdivision by remaining or secondary embankments influences the flooding process and pattern to a large degree. Only in dedicated case studies can this be assessed in sufficient detail by simulating various flood events. In the nationwide assessment, only a global judgement could be carried out, and this was only thanks to our job-related acquaintance with the many available flood simulations.

Evaluating the *potential* for cost-effectively splitting up the dike-ring areas meant a quest where at acceptable costs and without insuperable societal or ecological consequences, a new dividing embankment might be considered. Because investing in compartmentalisation may imply some competition with investing in reinforcing the flood defences all around, this meant a search for relatively elongated dike-ring areas: short dividing embankments are likely to be cheaper than long surrounding defences. But dike-ring areas that are bound by higher grounds on one or several sides may also qualify. The following criteria were taken into account:

- shape of the dike-ring area (elongated versus 'contained');
- orientation in relation to hazard source (splitting up is easier when the threat comes from one short side only);

Table 2 Some characteristics of the Netherlands' dike-ring areas: expected economic damage and expected number of fatalities (with lower and upper limits) due to flooding in the present situation (after Klijn *et al.*, 2007)

Dike ring area			Damage (10^6 euros)				Fatalities (no.)		
No.	Name	Surface area (ha)	Minimum	Expected	Maximum	People affected (no.)	Minimum	Expected	Maximum
1	Schiermonnikoog	824	50	90	90	800	0	1	4
2	Ameland	3224	150	300	300	3500	0	3	18
3	Terschelling	1880	100	200	200	1800	0	2	9
4	Vlieland	23	10	20	20	300	0	0	2
5	Texel	12 725	1200	2300	2300	14 000	1	13	70
6	Friesland en Groningen	493 513	55	600	1200	1 046 400	10	165	1256
7	Noordoostpolder	49 367	170	2100	4200	58 500	6	43	234
8	Flevoland	97 405	3500	7000	19 000	238 700	12	134	955
9	Vollenhove	50 645	1300	2650	5300	83 000	0	10	83
10	Mastenbroek	9546	750	1500	1500	32 200	0	4	32
11	IJsseldelta	11 651	600	1200	1200	45 400	0	7	45
12	Wieringen	22 336	1550	3100	3100	20 100	2	15	80
13	Noord-Holland	153 093	1800	3600	36 300	949 300	9	150	1139
14	Zuid-Holland	222 536	280	18 600	37 000	3 195 800	32	503	3835
15	Krimpenerwaard	31 812	2600	5100	10 200	195 400	16	106	586
16	Alblasserwaard	39 197	10 700	21 300	21 300	197 500	20	119	593
17	IJsselmonde	12 555	5100	10 100	20 200	335 300	34	251	1341
18	Pernis	154	300	500	500	4400	0	3	18
19	Rozenburg	305	700	1400	1400	13 600	1	10	54
20	Voorne-Putten	19 385	4500	9000	17 900	149 900	19	169	1124
21	Hoekse Waard	24 544	1600	3200	3200	82 900	4	37	249
22	Eiland van Dordrecht	4916	4500	9000	9000	98 200	10	74	393
24	Land van Altena	16 353	1200	2400	2400	51 100	5	31	153
23	Biesbosch		30	60	60				
25	Goeree-Overflakkee	22 458	1100	2100	4100	46 300	6	52	347
26	Schouwen Duivenland	22 094	1300	2500	5000	33 200	4	37	249
27	Tholen en St. Philipsland	13 878	700	1300	2500	22 700	1	10	68
28	Noord-Beveland	7753	200	400	700	6400	1	7	48
29	Walcheren	20 126	4000	8000	16 000	110 500	14	124	829
30	Zuid-Beveland west	26 089	2700	5300	10 500	69 900	9	79	524
31	Zuid-Beveland oost	7546	1200	2400	3400	18 800	2	21	141
32	Zeeuwsch Vlaanderen	71 862	500	900	17 700	105 700	1	20	159
33	Kreekrakpolder	1411	0	15	30				
34	West-Brabant	73 696	2800	5600	11 200	215 300	11	97	646
34-a	Geertruidenberg	358	100	200	200				
35	Donge	12 561	1800	3500	3500	87 400	9	52	262
36	Land van Heusden	73 153	60	3800	7500	400 200	0	35	400
36-a	Keent	104	0	0	0				
38	Bommelerwaard	10 887	1400	2800	2800	45 200	0	14	90
39	Alem	94	20	30	30				
40	Heerewaarden	236	20	40	40				
41	Land van Maas en Waal	27 929	2600	5200	5700	190 500	2	57	381
42	Ooij en Millingen	3433	500	1000	1000	10 700	0	3	21
43	Betuwe	62 595	4800	13 800	19 800	299 000	2	80	598
44	Kromme Rijn	63 484	2400	5500	17 000	592 700	6	71	533
45	Gelderse Vallei	32 470	900	5400	9000	247 300	20	134	742
46	Eempolder	1183	50	100	100	3500	0	3	14
47	Velpsebroek	2044	400	700	700	35 200	0	6	35
48	Rijn en IJssel	36 356	1600	4900	6600	186 100	1	44	372
49	IJsselland	8688	200	400	400	13 600	0	2	14
50	Zutphen	4089	900	1800	1800	39 500	0	5	40
51	Gorssel	4678	200	300	300	8000	0	1	8
52	Oost Veluwe	30 890	400	2100	3400	85 100	0	11	85
53	Salland	28 162	1900	5400	8700	185 900	1	23	186

- spatial distribution of vulnerable functions within the protected area (concentrated urban areas are easier to delimit than patchy developments); and
- existing major linear infrastructure (turning highway or railroad banks into dividing embankments may be cheaper than erecting entirely new embankments).

The results of the evaluations of relevance and potential (Figure 3) were combined into a final judgement on suitability ('attractiveness'; Figure 4). These figures seem to suggest that the majority of the country should be compartmentalised, but this is a bias caused by the fact that in a map the large dike-ring areas are the eye-catchers. In numbers, only eight of the 53 dike-rings are judged to require *serious consideration* for further subdivision, whereas for another 18 it *may be considered*. Half the dike-ring areas do not qualify at all.

Of the eight areas classified as most seriously, requiring further consideration, four have been selected as case studies for further investigation. They were selected not only by relative relevance but also in such a way that a variety of physiographical situations were covered, in order to allow extrapolation of the findings to the rest of the country.

Case studies

The following four case studies were investigated (see Figure 4 for the numbered locations): Flevoland (8); Central Holland (14); Land van Heusden (36); and Betuwe (43). It concerns dike-ring areas of different character.

Flevoland (8) is a deep polder area, part of the reclaimed Lake IJssel (former Southern Sea), where urban development is very rapid. The main city of Almere, mirroring Amsterdam, is intended to grow from about 170 000 inhabitants in the present situation to 350 000 by 2030. The primary aim of splitting up this polder is to prevent a large number of victims, as preventive evacuation of this area is practically impossible because of too little road capacity and too few bridges out of this insular polder area (Windhouwer, 2005).

Central Holland (14) is the most densely populated and economically important part of the country, which is threatened by various sources: the North Sea, the Rotterdam harbour area behind a storm surge barrier (Maeslandt barrier) and a Rhine River branch. Because of the significance of this area as the economic heart of the country, flooding could have enormous consequences for an area much bigger than the inundated area itself.

Land van Heusden (36) lies along the Meuse River, and is bound by an elevated Pleistocene sandy terrain on its southern side. This allows easy evacuation. Compartmentalisation would primarily be aimed at safeguarding the large but low lying city of 's Hertogenbosch and the A2, which is one of the country's key highways.

The Betuwe (43) is located between two Rhine River branches. It has a very elongated shape and is surrounded by $>$ 170 km of embankment. Being reclaimed from the Rhine River floodplain, it is definitely inclined towards the west,

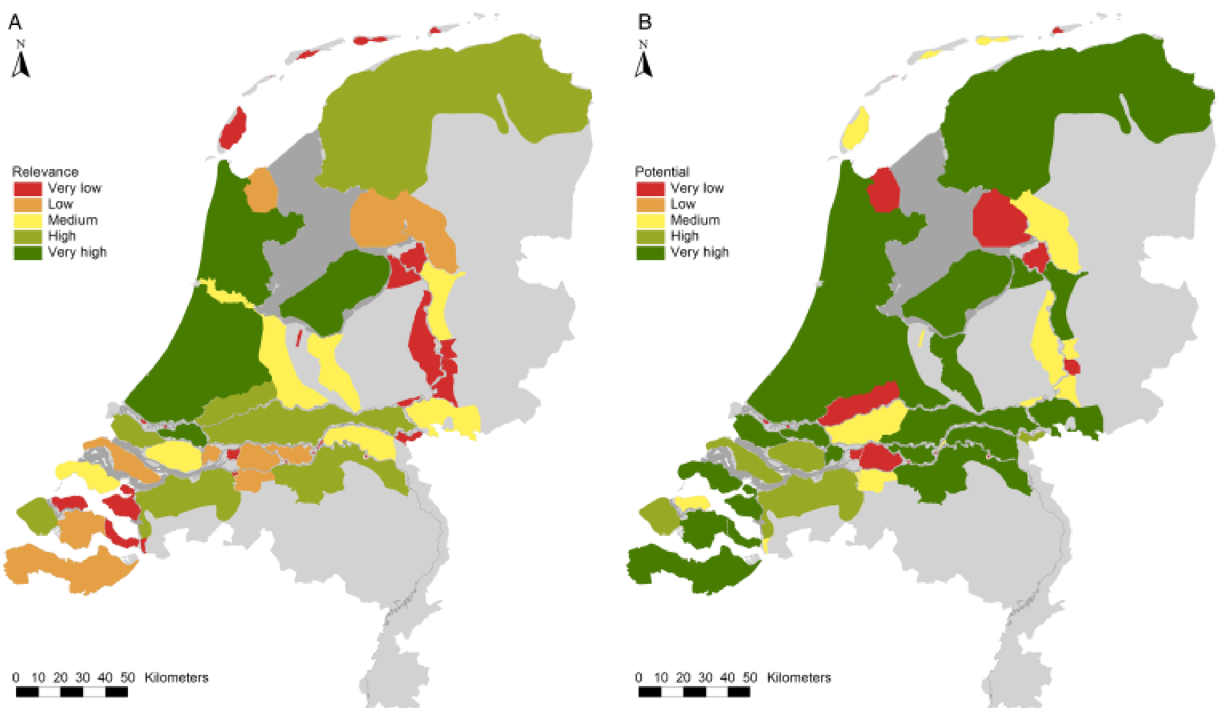


Figure 3 Assessment of (a) relevance and (b) potential of compartmentalisation per dike-ring area.

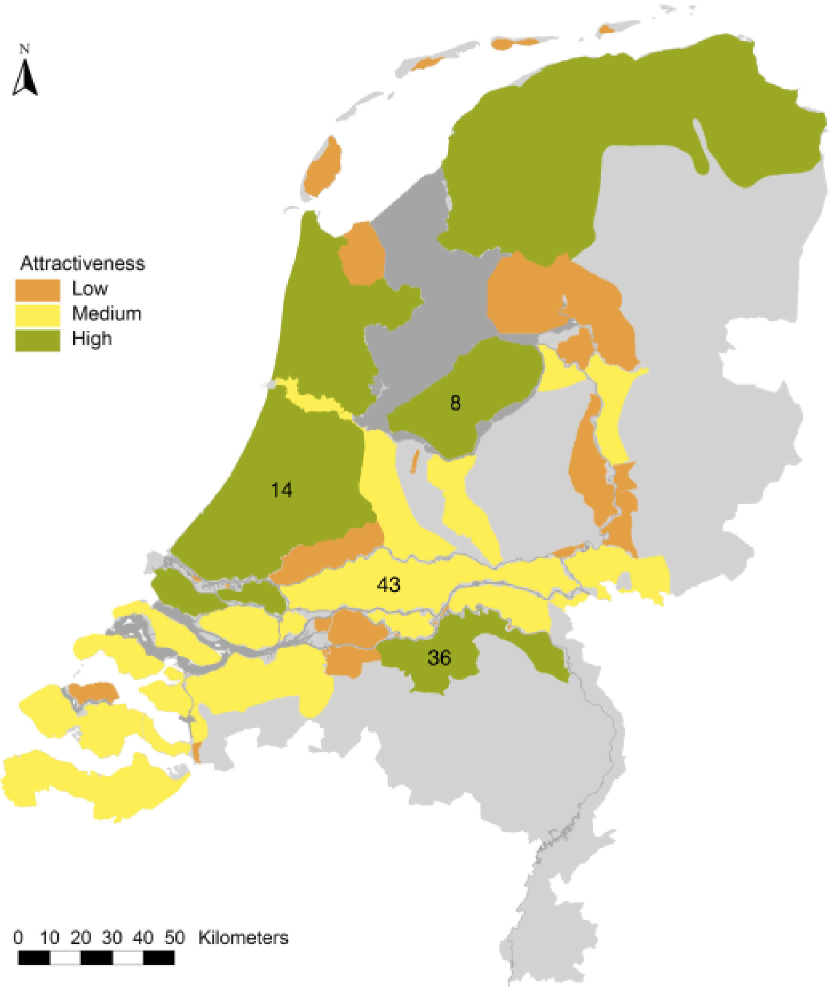


Figure 4 Final judgement of suitability ('attractiveness') of further subdividing dike-ring areas.

causing a flood from an upstream breach to keep flowing in for many days and the inundation to proceed to the furthest western end. This dike-ring area scores among the highest on the criterion of potential economic damage.

The aim of the case studies was, again, to determine whether, by which siting or plan, and under which conditions, compartmentalisation of these specific case-study areas would be sensible. At this spatial scale of analysis, the identification and assessment of alternative plans or sitings of compartmentalisation embankments was the main challenge. For each case, this involved a comparison of the situation in subdivided dike-ring areas with the situation in the present undivided dike-ring areas. For this comparison, it was assumed that all the embankments were well maintained, as the national law demands, and also updated for the effects of climate change, either through reinforcing the embankments or through the room-for-river measures to lower the design water levels (Van Stokkom and Witter, 2008). This assumption is important, because it determines the probability of flooding and, hence, the average annual risk reduction, as will be demonstrated and discussed later.

For the assessment of alternative plans, a set of criteria for sustainability assessment has been used, which was inspired by work on long-term planning for flood risk management (a.o. De Bruijn *et al.*, 1961; FLOODsite, 2009). The criteria comprised both flood risk-related criteria – such as expected annual damage, expected number of affected persons, expected number of fatalities – and unintended side-effects – for example, on natural and cultural landscape values or economic opportunities, as well as criteria for the capability to cope with uncertainties: robustness and flexibility (De Bruijn *et al.*, 1961). Monetary criteria, such as investment and maintenance costs and economic damage reduction, were combined into cost-effectiveness.

Some results from the case studies

For each case study, a number of alternative plans/sitings for embankments were investigated. Table 3 gives an overview of

Table 3 Overview of the benefits (for a representative event and annually) and benefit/cost ratio of all the investigated sites/routes (design probability refers to the protection standard, true probability refers to the expected flood probability according to Klijn *et al.*, 2007, which is often significantly lower)

Case-study area	Site/plan	Breach location/case	Benefit in case of flooding (109 euros)	Annual benefits (106 euros)		Costs (106 euros)	First year benefit/cost ratio in 2015	
				Design probability	'True' flood probability		Design probability	'True' flood probability
Betuwe	Betuwelinie	Bemmel	7.8	7.2	4.5	81	2.6	1.6
		Elden	−0.1	−0.2	−0.1	81	0.0	0.0
	Kesteren-Echteld	Bemmel	4.6	4.3	2.7	145	0.8	0.5
		Elden	−0.7	−0.6	−0.4	145	−0.2	−0.1
	ARK-W sluice Waal	Bemmel	14.2	13.3	8.3	87	4.3	2.7
		Elden	0.7	0.6	0.4	87	0.2	0.1
	ARK-W sluice NR/Lek	Bemmel	16.0	15.0	9.4	87	5.0	3.1
		Elden	1.7	1.6	1.0	87	0.5	0.3
Land van Heusden	HW east		6.5	6.1	3.2	141	1.3	0.8
	HW west		3.9	3.6	2.3	96	1.1	0.7
	Parallel_east		6.5	6.1	3.8	178	1.0	0.6
	Parallel_west		3.9	3.7	2.3	112	1.0	0.6
	RBSO		4.1	3.3	2.0	113	1.0	0.6
Flevoland	A27		8.5	2.9	1.2	350	0.2	0.1
	ZZ-Flevoland		8.7	3.0	1.2	346	0.3	0.1
	east of A6		7.3	2.4	1.0	258	0.3	0.1
	High Ring	With A27	8.5	2.9	1.1	389	0.2	0.1
	railway	With A27	10.4	3.4	1.4	195	0.4	0.2
Central Holland	Oude Maasdijk	Vluchtenburg	1.5	0.2	0.1	10	0.5	0.3
		Zijdijk-Zanddijk	1.5	0.2	0.1	11	0.5	0.3
	Hook of Holland – the Hague	N211	5.9	0.7	0.3	72	0.3	0.1
		West N211	5.9	0.7	0.3	63	0.3	0.2
	Katwijk	N206	4.4	0.5	0.3	162	0.1	0.1
		east N206	4.4	0.5	0.3	185	0.1	0.0
	Hollandsche IJssel	Without outlet	1.8	1.1	0.4	210	0.1	0.1
		With outlet	8.0	4.7	1.9	220	0.6	0.2
	Prinsendijk and Oude Rijndijk		0.1	0.1	0.0	383	0.0	0.0
	Amsterdam-Rijnkanaal	Entirely	−0.3	−0.3	0.0	89	−0.1	0.0
		South of Utrecht	−0.5	−0.5	0.0	28	−0.5	0.0

Significance: green, B/C ≥ 1.0; yellow, B/c 0.5–1.0; orange, B/c 0–0.5; red, B/c < 0.

the costs and economic benefits of all the investigated plans/sitings for all case studies, which are specified in the second column in Table 3. For some case studies, it also proved relevant to distinguish between different flood events, primarily determined by the breach location – some breaches causing much more inflow than others – or additional engineering works such as outlets (third column in Table 3).

The table shows the expected economic benefit in terms of damage avoided in case of flooding, as well as the annually damage avoided taking into account the probability of flooding. To estimate the annual economic benefit (columns 5 and 6), different assumptions on flood probability were applied: a flood probability equal to the protection standard – which is regarded an overestimate – and a flood probability that might be expected when the dikes are well kept and taking into account that design guidelines require that they are designed to withstand the design probabilities with at least 90% certainty. The latter would yield an actual flood probability of $<10\%$ of the probability of the design flood – which in turn would mean an underestimation of the importance of failure mechanisms other than overflow/overtopping.

For all case-study areas, it was found that, in case of flooding, a well-placed compartmentalisation embankment could substantially reduce the economic damage and the number of affected people, and might also significantly lower the number of fatalities. A reduction of the economic damage and the number of affected people of some 50–80% could be achieved in most case-study areas. The reduction of the number of fatalities is of the same order of magnitude, but we have not reported absolute numbers as they could not be quantified with sufficient certainty, as any loss-of-life estimate is very sensitive for assumptions on warning time and evacuation effectiveness – two very uncertain and heavily debated factors in our case (cf. also Jonkman, 2007; Lumbroso and Di Mauro, 2008; Lumbroso *et al.*, 2008).

The annual benefit of a dividing embankment in the Betuwe case, along the western side of a large shipping canal (from Amsterdam to the Rhine River), is the highest (8–13 million euros per year). In the Flevoland and Land van Heusden cases, an annual benefit of about 3–5 million euros can be expected, whereas the lowest annual benefit of compartmentalisation is achieved in the case-study area of Central Holland. This relates to the very low flood probability in this area ($<$1:10 000 per year).

The overall investment costs, including maintenance, vary from some 10 million euros for the reinforcement of an existing inland embankment (Oude Maasdijk) to almost 400 million euros for the heightening and reinforcement of the Prinsendijk and embankment along the Oude Rijn (Old Rhine), both in Central Holland, where it is difficult to divide the dike-ring area. Most compartmentalisation plans are, however, estimated to require an investment of between 100 and 200 million euros.

From a purely financial cost–benefit point of view – based on the first year benefit/cost ratio (using a discount rate of 2.5% and assuming the maintenance costs to amount 1% of the investment costs, and assuming 2% economic growth) – compartmentalisation would be an attractive flood risk reduction measure only in one of the cases, namely the Betuwe area. This is caused partly by the relatively low investment costs, but mainly by the large annual benefits. For the case Land van Heusden, the benefit/cost ratio is only >1.0 when it is assumed that the actual flood probability equals the protection level.

Whether compartmentalisation is an attractive measure in a case-study area or not does not depend only on the benefit/cost ratio. There may be very positive effects on intangibles, such as lower fatality risk or much fewer people affected by a flood, which make compartmentalisation desirable. This requires that the different plans/sitings of embankments are evaluated by a broader set of criteria, as they may have different side-effects, e.g. on the cultural and natural landscape, and may differ in robustness and flexibility, for example, because many openings for roads and railroads may endanger their well-functioning (less robust; Photo 2). Table 4 gives an example of such a full assessment for the three alternative sitings/plans for a dividing embankment through the Betuwe dike-ring area. It shows large differences on these qualitative, but societally very critical criteria.

What the case studies taught us

The case studies showed that each case-study area has its own specific complications, which requires a dedicated investigation; general principles seldom apply.

Firstly, it was confirmed that the pattern of existing embankments, road and railroad verges and other linear

Photo 2 Cuts through compartmentalisation embankments should be avoided and it should at least be possible to close them in time (Diefdijk, 20th century situation). This issue was taken into account when assessing the robustness of various siting alternatives.

infrastructure is of paramount importance to the flooding process (Alkema and Middelkoop, 2007), and hence also determines whether compartmentalisation has sufficient benefits. In Central Holland with its many ancient and secondary embankments, the flood spread is already effectively delimited, especially when it concerns a coastal flood caused by a storm surge; this lasts for <2 days, after which the external flood levels that determine the inflow through a breach already stay under the level of most secondary embankments (Figure 5). A key uncertainty we identified, however, is whether the secondary embankments will stand the flooding.

Secondly, our analyses revealed that in inclined areas along rivers, such as the Betuwe (Figure 6) and Land van Heusden, an outlet on the lower side of the dike-ring may substantially reduce the damage. The lower part of such dike-ring areas may become very deeply inundated, as any upstream breach will continue to flow in, while the flood water will flow through the area to the lower end. Especially when such dike-ring areas are split up, such an outlet is quintessential to lower the flood levels, as the flood levels may exceed the level of the embankments causing a knock-on effect on neighbouring polders. Also, the negative impact of greater depths on damage may then exceed the positive impact of the smaller flooded area (see the negative benefits for Betuwelinie and Kesteren-Echteld in Table 3).

Thirdly, fitting new or reinforced defense structures into an existing landscape without devastating the historically grown spatial quality, proved to be not so easy. In many cases, existing embankments are built-up on one or both sides, inhibiting their reinforcement without pulling down the majority of the houses. In such cases, entirely new embankments appeared easier to fit in, but these require either the design of an entirely new landscape, or planning a new embankment into the existing landscape with the least possible impacts. By involving landscape architects in the study, several good examples could be made, which enhanced the discussion with the local stakeholders (see Box 1).

Finally, and most importantly, we experienced that policy makers, stakeholders, and also the researchers were inclined to allocate maximum weight to the assessment criterion of economic cost/benefit ratio: the financial cost-effectiveness. This strongly influenced the preference for the most promising plan/siting of an embankment within a case, but also strongly affected the opinion of many policy makers on whether or not to consider compartmentalisation at all. There are two important issues related to this experience, however. Firstly, the annual benefit depends on the expected flood probability, which is very uncertain. And secondly, we obviously need to seriously and constantly take into account the trade-off between better flood protection and the reduction of consequences.

As to the first issue, we found it very difficult to quantify the annual benefits of compartmentalisation, because these are directly related to the probability of a flood event: a series of happenings from high water level (rare), dike failure, breach development, inflow and spread of water. The economic benefit doubles, if such an event does not have a probability of 1:2000 per year, but instead of 1:1000 per year, and it doubles again if it is 1:500 per year, etc. These may seem large differences, but they fall within the range of flood probabilities as estimated by known experts for the same place. And for such rare events as extreme floods, we cannot fall back on the measured probabilities; we have to rely on the few measurements available statistics, extrapolations, simulations and assumptions. In contrast, the estimates of investment and maintenance costs are much less uncertain. This means that the flood probability is the key variable that determines the benefit/cost ratio, or – in other words – that the benefit/cost ratio is very sensitive to the flood probability assumed.

As to the second, related issue, the tight correlation between flood probability and benefit/cost ratio means that in well-protected dike-ring areas, compartmentalisation would be much less desirable than in dike-ring areas with lower protection levels. In other words: ‘the better protected, the less profitable compartmentalisation’ (or whatever measure to reduce flood consequences). This would affect the answer to the question raised in an earlier section on where compartmentalisation would be attractive. And it implies that compartmentalisation must be evaluated not only by itself, but also in comparison with increasing flood protection standards as has already been done by the Ministry of Transport, Public Works and Water Management and Ministry of Interior and Kingdom Relations (2006; Kind, 2006), and even in comparison with further differentiating those which is still being

Table 4 Overview table of the assessment of the alternative plans/sitings for a compartmentalisation embankment in the Betuwe case study

Alternative plan/siting	Cost	Economic benefits	Threat to loss-of-life	Number of affected persons	Spatial quality	Robustness	Flexibility
Betuwelinie	–	+	–	++	++	–	– –
Kesteren-Echteld	– –	–	– –	++	–	– –	–
ARK-west	–	++	+	++	0	+	0

++, huge improvement/good; +, slight improvement/moderate; 0, neutral; –, slight decrease/inadequate; – –, huge decrease/poor.
Significance: green, B/C ≥ 1.0; yellow, B/c 0.5–1.0; orange, B/c 0–0.5; red, B/c < 0.

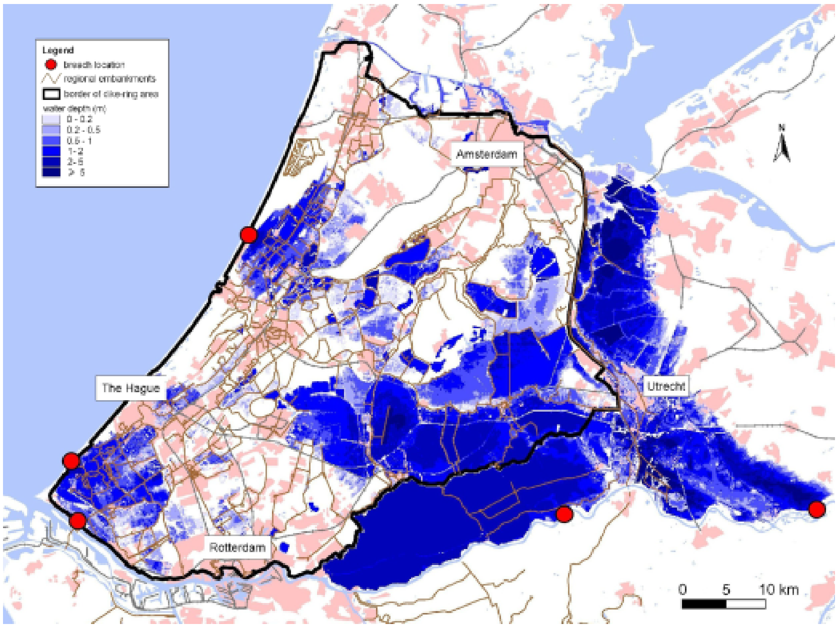


Figure 5 The maximum flood extent in Central Holland (dike-ring area 14) is effectively – though unintendedly – limited by existing secondary embankments and linear infrastructure in this case without additional compartmentalisation (all simulated breaches indicated with red dots and plotted on this one figure).

debated (Van der Most *et al.*, 2006). However, in the practice of the Netherlands' flood risk management, the best-protected areas are also the most vulnerable areas with the largest potential consequences in terms of damage and number of inhabitants. If a flooding would occur in any of those areas, the consequences would be tremendous and very likely unacceptable, both socially and politically.

Conclusions

The objective of the study was to answer the question as to whether compartmentalisation would be a sensible measure to reduce the consequences of flooding, and if yes, where and under which conditions. The reduction of flood risks is, in a densely populated and intensively used country like the Netherlands, quite a complicated task. This means that no simple answers can be given without compromising on nuances. Nevertheless, we shall share our main findings, without wandering into details.

On *whether* compartmentalisation is sensible:

1. Compartmentalisation is a proven concept to reduce the consequences of disasters in many risk situations.
2. It can effectively reduce the consequences of flooding in terms of damage done and number of people affected.
3. From a narrow economic perspective, it is cost-effective in only a few cases, due to the high protection standards maintained in the Netherlands.

On *where* compartmentalisation is sensible:

4. Subdividing polders is especially relevant when they are 'dangerously large' and easy to split up (elongated in shape).
5. The outcomes of the cost–benefit analyses in the various case studies strongly depend on the flood probability, which is only to be estimated with great uncertainty.
6. The judgement regarding which areas should preferably be subdivided is different when annual benefit (mean annual consequence reduction) is used as the criterion than when 'absolute' benefit (consequence reduction in case of an event) is used as the criterion.
7. For the case of Flevoland, it was found that no additional compartmentalisation embankments would qualify as being both cost-effective and robust. This is regarded as a conclusion that is representative for deep polders, such as those bordering Lake IJssel.
8. The further splitting up of Central Holland is not cost-effective, but its contribution to a reduction of consequences is very substantial and it may prevent societal disruption. This conclusion is regarded representative for all large flood-protected coastal plain areas in the Netherlands and abroad (Germany, United Kingdom, United States).
9. In the Netherlands' coastal plains, the benefits of compartmentalisation are relatively low because of the many existing ancient and secondary embankments and road and railroad verges, which effectively slow down the

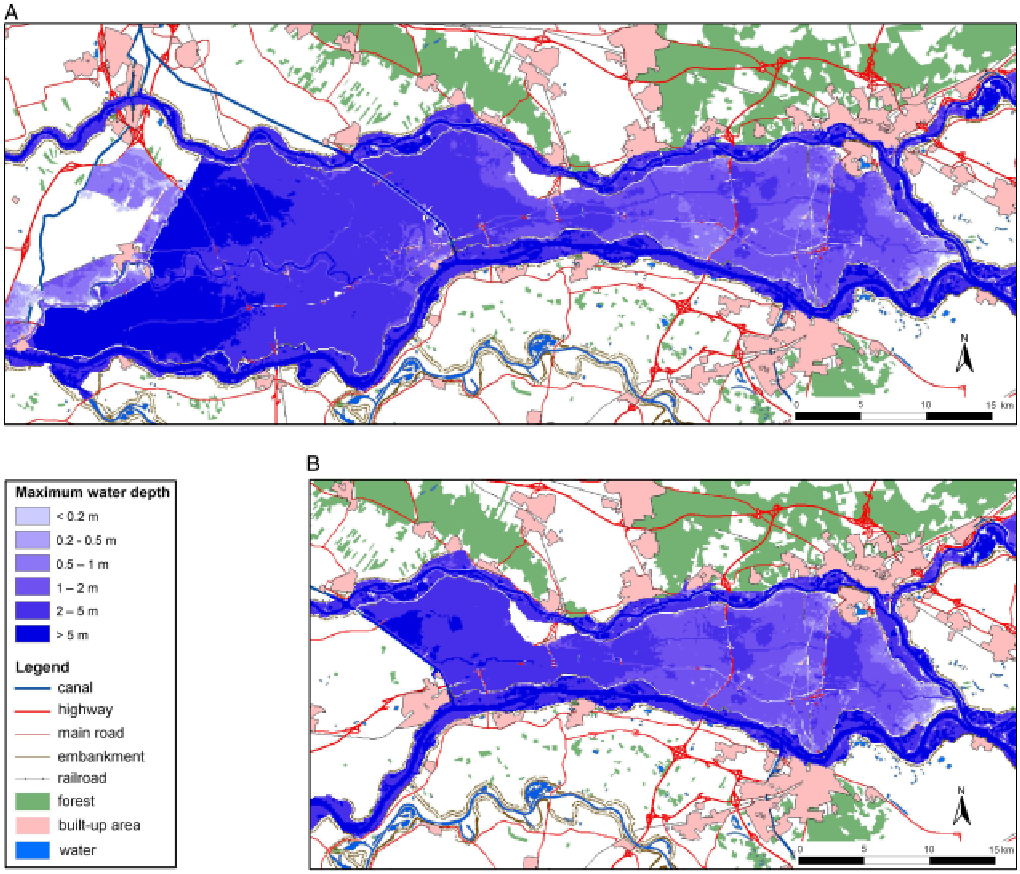


Figure 6 Water depth after a dike breach at the southwestern end (location Bemmel) resulting from a 1:1,250 years flood, without (a) and with (b) compartmentalisation along the Amsterdam-Rhine canal.

flooding process and delimit the flood's extent. The ability of these linear elements to withstand a prolonged period of flooding is, however, very uncertain and requires thorough investigation.

10. Subdividing the Land van Heusden can reduce the flood consequences by 50–80%. It is, however, very costly and not quite cost-effective.
11. In the Betuwe, a well-placed compartmentalisation embankment is both cost-effective and can be fitted in the existing landscape quite acceptably.

On the question, *under which circumstances* compartmentalisation is sensible:

12. Compartmentalisation is most effective in reducing flood consequences when combined with additional measures, such as a downstream outlet along rivers, differentiation of protection levels (better protection for urban area than for countryside), and evacuation planning.
13. A compartmentalisation embankment should be designed in such a way that it can also withstand conditions, which might occur after a breach resulting from above-design flood conditions, as otherwise a knock-down effect may occur with additional damage in compartments further downstream.

Reflection on policy perspectives

Our investigations were meant to support the ministry of Water Management and Public Works in its drafting of an update of the Netherlands' policy on flood risk management. The first outlines of this policy for the 21st century have recently been published in the draft National Water Plan (Ministry of Transport, Public Works and Water Management, 2008). It appears that the massive support of local and regional stakeholders for even better flood defences, despite their sometimes questionable cost-effectiveness, has had an appreciable influence on the government's preference to regard 'preventing floods' to be 'the cornerstone' of its flood risk management policy (pp. 6 and 69) and to give priority to spending money on that.

The study into compartmentalisation did, however, have a significant influence on the awareness among our policy

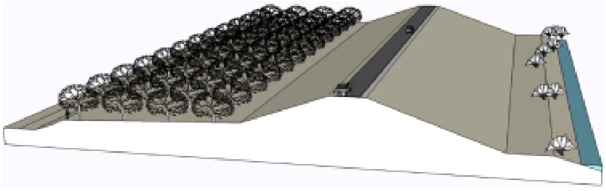
Box 1 Examples of landscape design for dividing embankments

In two case studies, landscape architects were involved, who facilitated the discussion with local stakeholders by visualising what each alternative plan might mean for their direct environment.

For Land van Heusden, one of the example designs involved an entirely new landscape between a new development of the city of 's-Hertogenbosch and the adjacent rural area. The dividing embankment in this case-study area aimed at protecting the vulnerable urban part better. A new embankment would visually detach the new urban development from the adjacent polder area. This drawback can be counteracted by designing it not as linear defence, but rather as an undulating landscape of a more sculptural character, whose lowest points still meet the design standards for flood defences. Such a landscape could function as the municipal park, with public gardens, pavilions, golf courses, skating sites and mountain-bike circuits.

Design: Bosch and Slabbers, landscape architects

For the Betuwe, one of the example designs involved the reinforcement and heightening of the existing embankment along the canal from Amsterdam to the Rhine River with 5 m. This canal already forms a visual and functional barrier in the area, but by a careful design of the cross-section and adjoining plantations, a much stronger embankment could be fitted in the existing landscape without any significant negative visual effect. Instead, the dike itself – especially when equipped with a road on top – might function as a grandstand to gain a view over the landscape of protected alluvial plains with its characteristic villages, the river floodplains with natural vegetation, and the intense shipping.



Design: Robbert de Koning landschapsarchitect bnt.

makers that the consequences of a flood – however rare – might be unacceptably high, both from a societal and from a political point of view, that is, not the flood risk, being the product of probability and consequence – which is very low – but the flood's consequence as such. And it was not so much the economic damage – of many billions of euros – but rather the possible number of fatalities that caused arousal (Table 2). In this sense, our study has triggered a debate on the question of whether or not a more fundamental statement is needed on the maximum acceptable consequences, specifically in terms of number of fatalities. This could then overrule the relatively 'unemotional' cost-effectiveness criterion. We see a similar fundamental approach in the case of fire risks and shipping, where in deciding on compartments or fire doors, cost-effectiveness no longer plays a role at all, but where a simple principle of maximum acceptable compartment size is applied, translated into building requirements. Such a debate might place compartmentalisation and other consequence-reducing measures more prominently on the policy agenda again.

References

Alkema D. & Middelkoop H. The influence of floodplain compartmentalization on flood risk within the Rhine-Meuse delta. Ch. 2. In: S. Begum, M.J.F. Stive, J.W. Hall & J.W. Hall, eds. *Flood risk management in Europe: innovation in policy and practice*. Springer, London, 2007, 21–42.

Asselman N.E.M. WINN-Verkenning compartimentering. Delft Hydraulics report Q4112, Delft, 2006.

De Bruijn K.M. Resilience and flood risk management. A systems approach applied to lowland rivers. Delft Hydraulics Select Series, no. 6, Delft, 2005.

De Bruijn K.M. & Klijn F. Risky places in the Netherlands: a first approximation for floods. *J Flood Risk Manag* 2009, **2**, 58–67.

De Bruijn K.M., Klijn F., McGahey C., Mens M. & Wolfert H. Long-term strategies for flood risk management: scenario definition and strategic alternative design. FLOODsite report T14-08-01, Delta Committee 1961.

De Bruine E.P. The influence of compartmentalisation on flooding in Central Holland. MSc Thesis, TU-Delft, 2006.

EU. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. OJEU L 288/27 (6.11.2007), 2007.

FLOODsite. Language of risk. Project definitions. Report T32-04-0. Available at http://www.floodsite.net, 2005.

FLOODsite. *Flood risk assessment and flood risk management. An introduction and guidance based on experiences and findings of FLOODsite (an EU-funded Integrated Project)*. Delft, the Netherlands: Deltares | Delft Hydraulics, 2009, 140pp. Available at http://www.floodsite.net.

Gerritsen H. What happened in 1953? The big flood in the Netherlands in retrospect. *Philos Trans Roy Soc* 2005, **363**, (1831), 1271–1291.

Jonkman S.N. Loss of life estimation in flood risk assessment. Theory and applications. PhD Thesis, Delft University of Technology, Delft, 2007.

Jonkman S.N., Boèkarjova M., Kok M. & Bernardini P. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecol Econ* 2008, **66**, (1), 77–90.

Kind J. Kosten-batenanalyse Rampenbeheersingsstrategie Overstromingen Rijn en Maas. Report Rijkswaterstaat-RIZA, 2006.

Kind J., Gauderis J., Van Velzen E. & Silva W. Kengetallen Kosten-batenanalyse Waterveiligheid 21^{e} eeuw. Report WD 2008.044, Ministry of Water management and Public Works, 2008.

Klijn F., Baan P., De Bruijn K.M. & Kwadijk J. Overstromingsrisico's in Nederland in een veranderend klimaat; verwachtingen, schattingen en berekeningen voor het project Nederland Later. WL-Report Q4290, Delft, 2007.

Klijn F., Samuels P. & Van Os A. Towards flood risk management in the EU: state of affairs with examples from various European countries. *J River Basin Manag* 2008, **6**, (4), 307–321.

Klijn F., van der Klis H., Stijnen J., de Bruijn K. & Kok M. Overstromingsrisico dijkringen in Nederland; betooglijn en deskundigenoordeel. WL-Report Q3503.10, Delft, 2004.

Kok M., Silva W., Slomp R. & Stijnen J.W. River management and flood risk reduction using structural measures and disaster management for the Rhine river in the Netherlands. Proceedings of the ISSH Stochastic Hydraulics 2005, 23 and 24 May, Nijmegen, the Netherlands, 2005.

Lumbroso D. & Di Mauro M. Recent developments in loss of life modelling for flood event management in the UK. In: D. Proverbs, C.A. Brebbia & E. Penning-Rowsell, eds. *Flood recovery, innovation and response*. Southampton: WIT Press, 2008.

Lumbroso D., Gaume E., Logtmeijer C., Mens M. & Van der Vat M. Evacuation and traffic management, FLOODsite Task 17, Report number T17-07-02, HR Wallingford, Wallingford, UK, 2008.

Ministry of Transport, Public Works and Water Management. *Nationaal WaterPlan, ontwerp (in Dutch: National Water Plan, proposal)*. the Hague: Ministry of Transport, Public Works and Water Management, 2008.

Ministry of Transport, Public Works and Water Management and Ministry of Interior and Kingdom Relations. *Eindrapport onderzoeksprogramma Rampenbeheersingsstrategie Overstromingen Rijn en Maas*. the Hague: Ministry of Transport, Public Works and Water Management and Ministry of Interior and Kingdom Relations, 2006.

Rijkswaterstaat and KNMI. *Verslag over de stormvloed van 1953*. 's-Gravenhage: Staatsdrukkerij en uitgeversbedrijf, 1961.

Samuels P., Klijn F. & Dijkman J.P.M. River Flood Risk management policies in different parts of the world: synthesis of a special session by NCR. In: Floods, from Defence to Management Symposium Proceedings. Taylor and Francis Group, 2006, 73–81.

Samuels P.G., Morris M.W., Sayers P., Creutin J.-D., Kortenhaus A., Klijn F., Mosselman E., Van Os A. & Schanze J. Advances in flood risk management from the FLOODsite project. In: P.G. Samuels, *et al*. eds. *Flood risk management: research and practice*. London: Taylor & Francis Group, 2009, 433–443.

Theunissen R.P.G.J. A probabilistic flood risk assessment and the impact of compartmentation. MSc Thesis TU-Delft, 2006.

Van der Most H., Baan P. & Klijn F. Differentiatie in bescherming tegen overstroming? Discussiestuk voor 'Waterveiligheid 21^{e} eeuw'. WL-Report Q4044/Q4143, Delft, 2006.

Van Heezik A. Battle over the rivers. Two hundred years of river policy in the Netherlands, Haarlem and the Hague. PhD Thesis, TU Delft, 2008a.

Van Heezik A. Het voordeel eener dubbel defensie. De discussies rond het compartimenteren van dijkringen in het verleden. Deltares Report T2513.20, Delft, 2008b.

Van Stokkom H.T.C. & Witter J.V. Implementing integrated flood risk and land-use management strategies in developed deltaic regions, exemplified by the Netherlands. *J River Basin Manag* 2008, **6**, (4), 331–338.

Verwijmeren P. Gevolgen van overstromen. Onderzoek naar maatregelen ter reductie van overstromingsschade. MSc Thesis, TU Delft, 106+52pp, 2002.

Vis M., Klijn F., De Bruijn K.M. & Van Buuren M. Resilience strategies for flood risk management in the Netherlands. *J River Basin Manag* 2003, **1**, (1), 33–40.

Windhouwer C.J. Evacuatiestrategieën Provincie Flevoland: een eerste verkenning. Oranjewoud Report 152117, 2005.